Travel-Time Sensitivity Kernels in Long-Range Propagation

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LONG-TERM GOALS

Our long-term goal is to develop reliable tools for modeling the sensitivity of travel-time observables to sound-speed perturbations in low-frequency long-range acoustic propagation in the ocean and associated tomography experiments.

OBJECTIVES

Our primary objective is to use the wave-theoretic travel-time sensitivity kernel (TSK) in order to study the effect of increasing range on the sensitivity of finite-frequency travel-time observables to sound-speed perturbations. A further objective is to compare wave-theoretic TSKs and Fresnel volumes associated with particular eigenrays, seeking connections between the ray-theoretic and wave-theoretic description of travel-time observables.

APPROACH

To study the effect of increasing range on the sensitivity of finite-frequency travel times we make use of the wave-theoretic TSK introduced by Skarsoulis and Cornuelle (2004) based upon the first Born approximation for perturbations of the Green's function and the notion of peak arrivals (Athanassoulis and Skarsoulis 1994). The wave-theoretic TSK represents the effect that a sound-speed change at any location in the medium has on finite-frequency travel times. To establish a bridge between wave-theoretic and ray-theoretic sensitivity, we calculate ray-theoretic Fresnel volumes taking into account the effects of refraction (Kravtsov and Orlov 1990) and compare them with the corresponding wave-theoretic TSKs. The latter are calculated assuming a range-independent background environment and using normal-mode theory in 2 and 3 dimensions.

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14. ABSTRACT
Our long-term goal is to develop reliable tools for modeling the sensitivity of travel-time observables to sound-speed perturbations in low-frequency long-range acoustic propagation in the ocean and associated tomography experiments.

15. SUBJECT TERMS

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Particularly, for the range-independent problem, in which both the background and the perturbed environment are range-independent, we calculate depth TSKs representing the effect that a sound-speed change at any depth has on finite-frequency travel times. This calculation is carried out by applying perturbation theory to the normal-mode representation of the Green's function in 2 and 3 dimensions. We study the effect of dimensionality by comparing the resulting 2D and 3D kernels. Further, to assess the effect of increasing range, we compare wave-theoretic depth TSKs with the corresponding ray-theoretic kernels for different propagation ranges.

WORK COMPLETED

In the second year of the project we carried out ray-theoretic calculations of Fresnel volumes in stratified media and compared them with wave-theoretic TSKs for various ranges. Further, for the range-independent case, we calculated and compared wave-theoretic and ray-theoretic depth TSKs for various ranges, revealing a convergence of the wave-theoretic results towards the ray theoretic ones as the range increases, even for low frequencies. Finally, we carried out comparisons between wave-theoretic depth TSKs based on 3D and 2D normal-mode representations.

RESULTS

Some numerical results are presented in the following. They all refer to a model environment characterized by water depth of 2500 m, linear sound-speed profile in the water (1503 m/s at the surface, 1547 m/s at 2500-m depth), and absorbing bottom (half space of unit density and constant sound speed, equal to the water sound speed at the water-bottom interface) with sufficient attenuation to suppress bottom-related arrivals (Skarsoulis and Cornuelle 2007). Both source and receiver are considered at a depth of 150 m and at various ranges. The signal emitted by the source is taken to be a Gaussian pulse of 100-Hz central frequency and 60-Hz bandwidth (3-dB bandwidth).

Comparison of wave-theoretic TSKs and Fresnel volumes

Fig. 1 shows vertical sections (in the source/receiver vertical plane) of the 3D wave-theoretic TSK (in color) and the Fresnel volumes (black solid lines) corresponding to early arrivals for source-receiver ranges of 30, 100, 250, 500, 1000 and 1500 km. For the longer propagation ranges (>100 km) the figures focus on the first 100 km presenting in detail the extent of the sensitivity areas about the eigenrays (marked by the dashed lines).

For the range of 30 km the banana-doughnut stereotype is reproduced with the kernel concentrated about the corresponding eigenray with zero sensitivity on the eigenray, negative sensitivity at a distance and positive sensitivity further out. The boundary of the Fresnel volume coincides with the positive sensitivity area of the TSK, in agreement with the anticipated behavior in free space (Skarsoulis and Cornuelle 2004). At a range of 100 km the TSK contracts in the vertical and comes closer to the eigenray with simultaneous reduction of the zero-sensitivity core. For longer ranges, starting with 250 km, the zero-sensitivity cores disappear leaving an area of near uniform negative sensitivity in the vicinity of the eigenrays.

The Fresnel volumes behave similarly to the wave-theoretic TSKs with increasing range and they are in remarkable agreement to them, as far as their extent is concerned, the Fresnel volumes enclosing the domains of negative wave-theoretic sensitivity. Of course the TSKs give a more detailed description of the sensitivity areas about the eigenrays. Nevertheless as the range increases the sensitivity distribution

about the eigenray becomes more regular (uniformly negative) and in this connection the difference between the TSK and the Fresnel volume more insignificant.

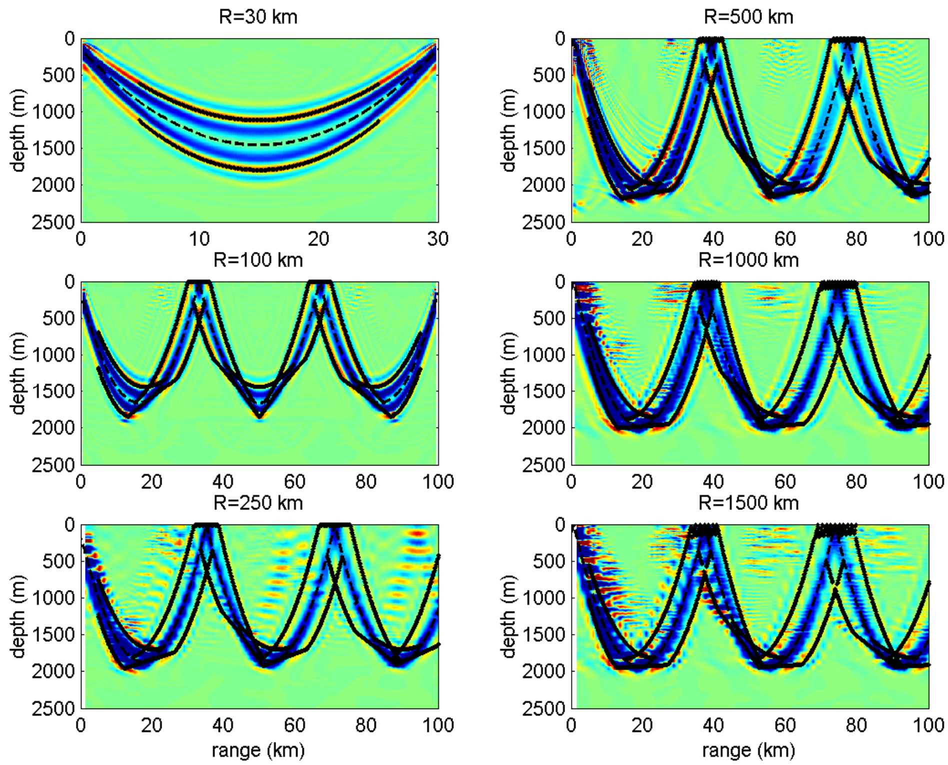

Fig. 1. Vertical sections of wave-theoretic TSKs (in color) and Fresnel volumes (solid lines) about eigenrays (dashed lines) corresponding to early arrivals, for propagation ranges between 30 and 1500 km, focusing on the first 100 km.

TSKs in 2D and 3D

Fig. 2 shows the predicted arrival pattern (top panel) and the sensitivity kernels (lower panels) for the first three arrivals for source/receiver range of 100 km. The results on the left are based on the 3D representation of the Green's function in terms of normal modes, whereas the ones on the right are based on the 2D representation (Jensen et al. 2000). It is evident that the 2D TSKs are different from the corresponding 3D TSKs. One main difference is the travel-time sensitivity in the immediate vicinity of the eigenray: it is near zero in the 3D case, at least close to the turning points, but nonzero in the 2D case; a similar difference between 2D and 3D TSKs has been observed by Marquering et al.(1999) for seismic phase arrivals. A further difference has to do with the concentration of sensitivity domains about the eigenray: the 3D TSK is thicker than the 2D TSK about the turning points but thinner elsewhere.

Relying on Fig. 2 one cannot answer the question how significant the above differences are when applied to sound-speed perturbations and integrated over the 2D and 3D space, respectively. The reason is that Fig. 2 while describing the entire 2D TSK only gives a vertical section of the 3D TSK. A way to answer the question is by taking horizontal marginals of the 2D and 3D TSK or equivalently by addressing the range-independent problem in 2 and 3 dimensions.

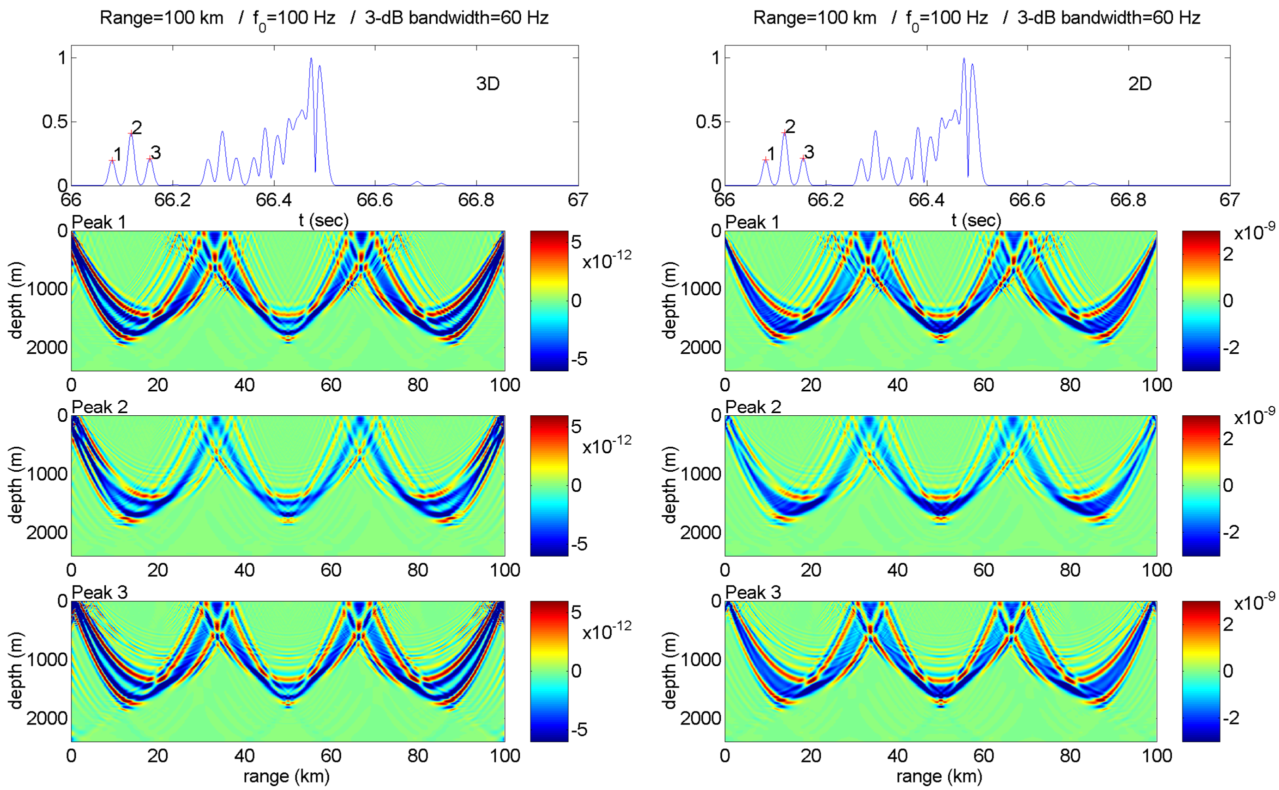

Fig. 2. Arrival patterns and wave-theoretic TSKs in the 3D (left) and 2D (right) case for propagation range of 100 km.

Depth TSKs

In the case of range-independent sound-speed perturbations it turns out that the above difference between 2D and 3D kernels is not significant. To show this we calculate depth TSKs in 2 and 3 dimensions, representing the effect that a perturbation of the sound-speed profile at any depth will have on the peak arrival times. These calculations are carried out by applying perturbation theory to the normal-mode representation of the 2D and 3D Green's function, respectively. Fig. 3 shows the 2D arrival pattern for propagation range of 100 km and the depth TSKs for the first three arrivals in the 2D case (in blue) and the 3D case (in red). These kernels are equal to the marginals of the 2D and 3D TSKs (Fig. 2) with respect to the horizontal. The 2D and 3D depth TSKs in Fig. 3 are in stunning agreement with each other. This means that the differences between the 2D and 3D kernels appearing in Fig. 2 can be disregarded if one is interested in range-independent perturbations or perturbations of large horizontal scales.

Effects of increasing range on depth TSKs

In the following we focus on the effect of increasing range on depth TSKs. Fig. 4 shows a comparison of wave-theoretic (in blue) and ray-theoretic (in red) depth TSKs for source-receiver ranges of 30, 100, 250, 500, 1000 and 1500 km. The support of the ray-theoretic sensitivity kernels extends from the sea surface (upper turning depth) to the corresponding lower turning depth, at which depth they attain their maximum. The wave-theoretic depth TSK for the range of 30 km exhibits significant deviations from

the ray-theoretic kernel, both in the amplitude and the vertical extent: While the ray-theoretic sensitivity is strictly negative, corresponding to the physical expectation that a sound-speed increase should cause a travel-time decrease, the wave-theoretic depth TSK though mainly negative takes also positive values over certain depth intervals. Thus, in the wave-theoretic context a sound-speed increase may also cause a travel-time increase if it takes place around a depth of positive sensitivity. Further, the wave-theoretic TSK extends by more than 500 m below the ray-theoretic turning depth, which means that finite-frequency travel times are sensitive to sound-speed changes taking place at depths far beyond the ray-theoretic turning depth.

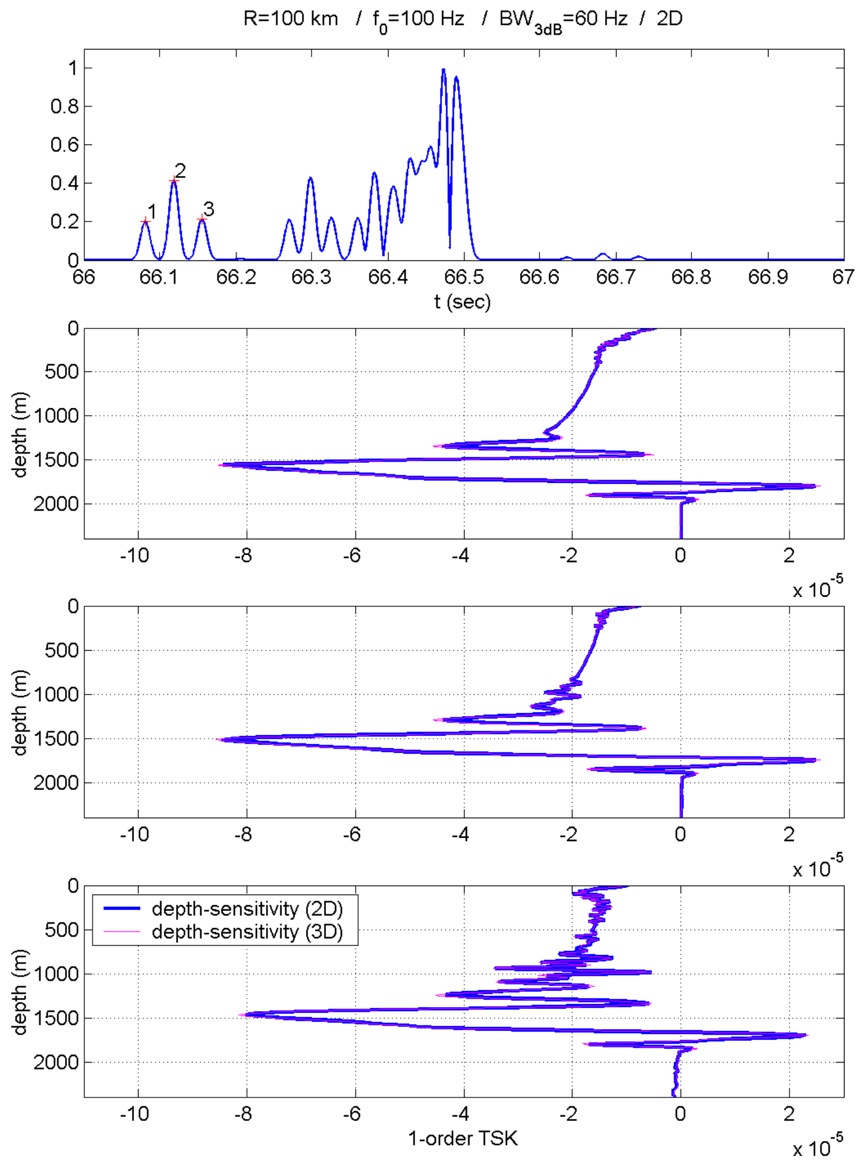

Fig. 3. Arrival pattern and depth TSKs in the 3D and 2D case for propagation range of 100 km.

Coming to the effect of increasing range, from Fig. 4 it is seen that as the propagation range becomes longer the wave-theoretic depth sensitivity approaches the ray-theoretic sensitivity. For ranges beyond 500 km the two sensitivity kernels appear to be very close to each other, and this happens despite the fact that the propagation frequency is low (100 Hz). This finding suggests that increasing the range has a similar effect as increasing the frequency, and that for long range propagation ray-theoretic depth TSKs can be applied even for low frequencies in a range-independent framework.

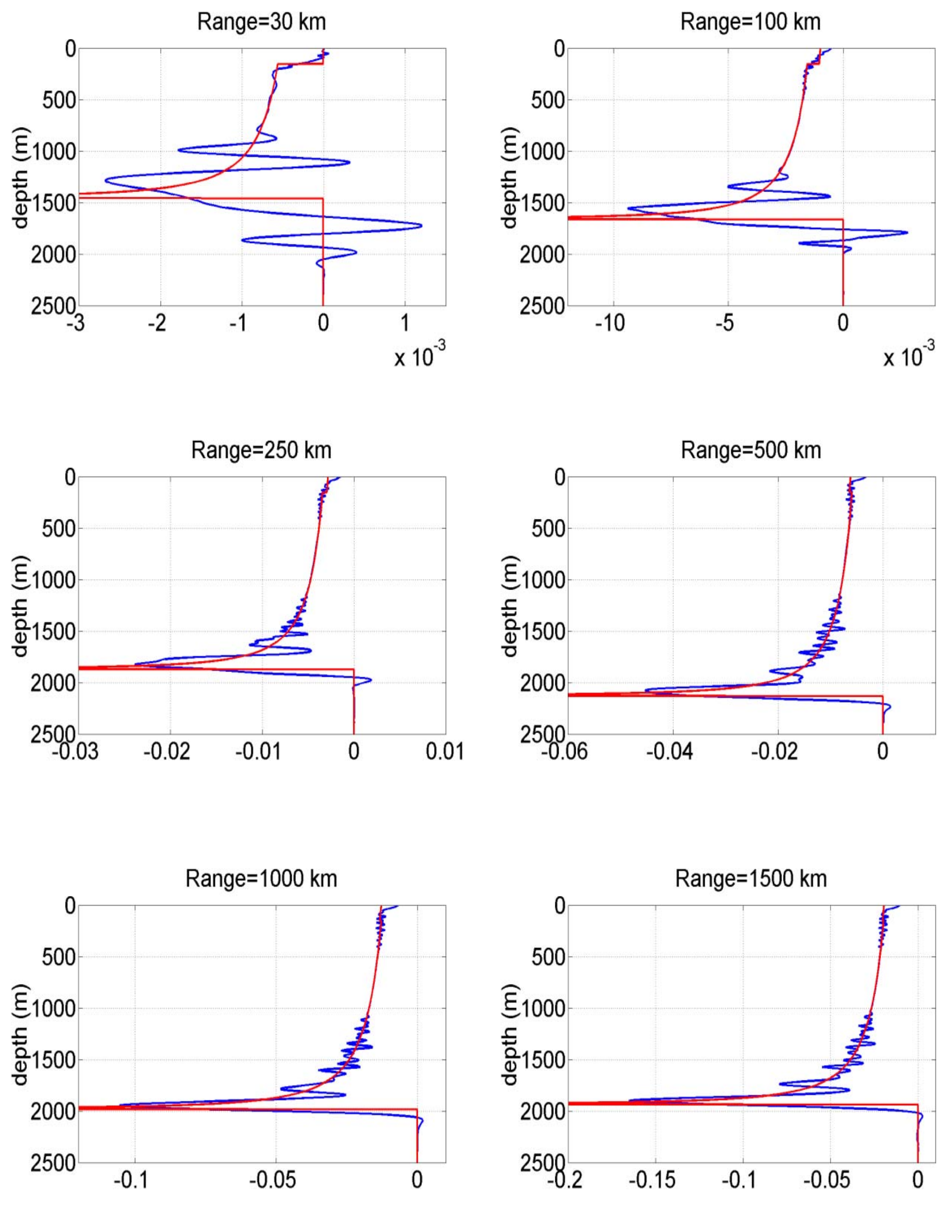

Fig. 4. Wave-theoretic (blue) and ray-theoretic (red) depth TSKs corresponding to early arrivals, for propagation ranges between 30 and 1500 km.

IMPACT/APPLICATIONS

The results from the second year of the project offer further support to the use of ray theory for interpretation of long-range transmissions even at low frequencies: the convergence of the TSK in the vertical towards the eigenray, especially close to the turning points, combined with the expansion in the horizontal as the range increases, and further the good agreement between wave-theoretic TSKs and Fresnel volumes, indicates that wave-theoretic travel times are sensitive to sound-speed changes on the eigenrays and their horizontal (cross-range) neighborhood over Fresnel scales. This is further reinforced by the convergence with increasing range of wave-theoretic depth TSKs towards the corresponding ray-theoretic ones for range-independent problems.

RELATED PROJECTS

In the framework of NPAL (ONR contract N000140310182) Bruce Cornuelle and Matthew Dzieciuch are exploring the spatial frequency content and the stability of TSKs in range-dependent ocean environments which produce strong sensitivity of ray paths to initial conditions.

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